

Nitrogen Removal from Municipal Wastewater

Research Report No. 17

TD
758.5
.N58
C55

**Research Program for the Abatement of Municipal Pollution
under Provisions of the Canada-Ontario Agreement
on Great Lakes Water Quality**

Copyright Provisions and Restrictions on Copying:

This Ontario Ministry of the Environment work is protected by Crown copyright (unless otherwise indicated), which is held by the Queen's Printer for Ontario. It may be reproduced for non-commercial purposes if credit is given and Crown copyright is acknowledged.

It may not be reproduced, in all or in part, part, for any commercial purpose except under a licence from the Queen's Printer for Ontario.

For information on reproducing Government of Ontario works, please contact Service Ontario Publications at copyright@ontario.ca

CANADA-ONTARIO AGREEMENT

RESEARCH REPORTS

These RESEARCH REPORTS describe the results of investigations funded under the Research Program for the Abatement of Municipal Pollution within the provisions of the Canada-Ontario Agreement on Great Lakes Water Quality. They provide a central source of information on the studies carried out in this program through in-house projects by both Environment Canada and the Ontario Ministry of the Environment, and contracts with municipalities, research institutions and industrial organizations.

The Scientific Liaison Officer for this project was Dr. B.E. Jank, Environment Canada.

Enquiries pertaining to the Canada-Ontario Agreement RESEARCH PROGRAM should be directed to -

Wastewater Technology Centre,
Canada Centre for Inland Waters,
Environment Canada,
P.O. Box 5050,
Burlington, Ontario L7R 4A6

Ontario Ministry of the Environment,
Pollution Control Branch,
135 St. Clair Avenue West,
Toronto, Ontario M4V 1P5

TD
758.5
.N58
C55

Nitrogen removal from
municipal wastewater /
Climenhage, D. C.

78887

NITROGEN REMOVAL FROM MUNICIPAL WASTEWATER

by

D.C. Climenhage
Senior Process Chemist
Du Pont of Canada Limited

RESEARCH PROGRAM FOR THE ABATEMENT
OF MUNICIPAL POLLUTION UNDER THE
PROVISIONS OF THE CANADA-ONTARIO
AGREEMENT ON GREAT LAKES WATER QUALITY

Project No. 72-5-15

This document may be obtained from -

Training and Technology Transfer
Division (Water)
Environmental Protection Service
Environment Canada
Ottawa, Ontario
K1A 0H3

Ontario Ministry of the Environment
Pollution Control Branch
135 St. Clair Avenue West
Toronto, Ontario
M4V 1P5

REVIEW NOTICE

This report has been reviewed by the Technical Committee of the Canada-Ontario Agreement on Great Lakes Water Quality and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of either the Ontario Ministry of the Environment or Environment Canada, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

A pilot plant evaluation was completed on a nitrification-denitrification process for nitrogen and BOD removal. The process was designed to eliminate the need for carbon addition to the denitrification stage by utilizing carbon from sewage influent for denitrification.

The Maitland Works of Du Pont of Canada Maitland, Ontario 50,000 gpd extended aeration sewage treatment plant was used for this study. The plant was modified to provide a denitrification stage ahead of the aeration tank and a pump to recycle mixed liquor from the aeration tank back to the denitrification stage at 0.5 to 4 times the raw sewage feed flow.

Initial attempts at start-up were unsuccessful because of mechanical difficulties and further modifications were made. Following these changes the system was started up and continuous operation was established.

The actual organic loading for the extended aeration treatment plant was much less than the plant was designed for as the domestic wastewater at the plant site had a very low BOD. A 50% mixture by volume of hexamethylene diamine and methanol was metered into the raw sewage feed to increase the BOD and organic nitrogen concentration. About 75% of the BOD and nitrogen content of the feed was contributed by diamine and methanol.

A total nitrogen removal in excess of 85% was demonstrated at recycle ratios of 1:1 to 1.5:1 times the raw sewage flow based on total influent and filtered effluent nitrogen.

RÉSUMÉ

On a terminé une évaluation en unité pilote d'un procédé de nitrification suivie de dénitrification, permettant l'élimination de l'azote et de la DBO. Le procédé visait à éliminer une addition de carbone pour le stade de la dénitrification, grâce à l'emploi du carbone présent dans l'influent d'eau usée.

Pour l'étude, on a utilisé l'installation de traitement des eaux usées par oxydation prolongée, de la Maitland Works, dont le débit de travail était de 50,000 gallons par jour. Cette installation fut modifiée pour permettre la dénitrification de l'effluent avant son séjour dans le bassin d'aération, et on l'a pourvue d'une pompe pour le recyclage de la liqueur mixte du bassin d'aération vers le dispositif de dénitrification, à raison de 0.5 à 4 fois le débit d'arrivée des eaux usées brutes.

À cause d'ennuis mécaniques, les premiers essais de démarrage se sont soldés par des échecs; on a dû procéder à d'autres modifications, après quoi, le système a pu démarrer et fonctionner sans arrêt.

La charge organique effective appliquée à l'installation était bien inférieure à la charge pour laquelle elle avait été conçue; en effet, la DBO des eaux usées domestiques traitées était très faible. Afin d'augmenter la DBO et la concentration en azote organique, on a ajouté en quantités mesurées un mélange de 50% en volume de méthanol et d'hexaméthylènediamine dans l'eau usée brute d'apport. Ainsi 75% de la DBO et de l'azote étaient attributables à la présence du méthanol et de la diamine ajoutés.

On a obtenu un rendement supérieur à 85% pour l'élimination de l'azote total pour des débits de recyclage égaux ou jusqu'à 1.5 fois supérieurs au débit des eaux usées brutes. Ce rendement a été calculé d'après la teneur totale en azote, soit dans l'influent et dans l'effluent filtré.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	i
TABLE OF CONTENTS	iii
List of Figures	iv
List of Tables	iv
CONCLUSIONS	v
RECOMMENDATIONS	v
1. INTRODUCTION	1
1.1 Objective	1
2. LITERATURE REVIEW	3
2.1 Nitrogen Content of Sewage	3
2.2 Alternate Methods of Nitrogen Removal	3
2.3 Denitrification	3
3. EQUIPMENT AND METHODS	9
3.1 Existing Equipment	9
3.2 Equipment Modifications	9
3.3 Start-Up Problems	13
3.4 Sampling and Analytical Techniques	13
4. RESULTS AND DISCUSSION	15
4.1 Process Performance	15
4.2 Possible Explanation of High Nitrogen Removal	24
ACKNOWLEDGEMENT	30
REFERENCES	31

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Du Pont of Canada Process	2
2	Nitrate Reduced in 48 Hours in Aerobic Cultures as a Percentage of that in Anaerobic Cultures	6
3	Three Sludge System for Nitrogen Removal	7
4	Flow Diagram - Existing Treatment Plant	12
5	Flow Diagram - Modified Treatment for "N" Removal	12
6	Process Performance	22

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Performance Data Conventional Operation	10
2	Test Operating Conditions	16
3	Analytical Results	19
4	Analytical Result of Low and Zero Recycle	25
5	Test Operating Conditions at Low and Zero Recycle Ratios.	27

CONCLUSIONS

1. An overall nitrogen removal efficiency of 85 - 90% was demonstrated on waste that was approximately 25% sewage and 75% chemical supplement consisting of a mixture of hexamethylene diamine and methanol. These efficiencies were based on total nitrogen in the influent and filtered effluent and were achieved with recycle to feed ratios of 1:1 to 1.5:1. The tests were carried out with the influent at a temperature of 10°C.
2. Approximately 18% nitrogen removal was accounted for by recycle to the anaerobic first stage. Approximately 13% nitrogen removal was accounted for by cell synthesis. The mechanism for the remaining 55 - 60% removal could not be accounted for in this experiment.

RECOMMENDATIONS

1. Further test work should be carried out to confirm the results with full strength sewage (i.e. without the synthetic hexamethylene diamine/methanol supplement). This cannot be done with the sewage generated at the Maitland Works of Du Pont of Canada Ltd.
2. Further test work should be completed on the process to investigate the mechanism of nitrogen removal and the effect of key parameters on nitrogen removal efficiency.

1. INTRODUCTION

It has been recognized in the International Joint Commission Report 1969, that phosphate removal alone may not completely solve the problem of eutrophication in the Great Lakes. It may be necessary to provide treatment to remove nitrogen as well. In addition to its nutrient effect, ammonia nitrogen exerts a nitrogenous oxygen demand on the receiving water.

Du Pont of Canada Limited has, within the past three years, developed a biological treatment process to remove nitrogen, as well as organic carbon compounds, from the industrial wastewater of its Maitland Works. The flowsheet being tested has the denitrification stage first, followed by an extended aeration stage that achieves BOD reduction and nitrification. Mixed liquor from the aerated stage is recycled at a high rate to the anaerobic stage where nitrate is denitrified using the sewage as an organic carbon source. (See Figure 1) The major advantage of this process for nitrogen removal is that the required addition of organic carbon, usually in the form of methanol, for denitrification is eliminated.

1.1 Objective

The objective of this study was to evaluate this nitrogen removal process for the treatment of municipal sewage at mixed liquor recycle rates of 0.5 to 4 times the raw sewage flow.

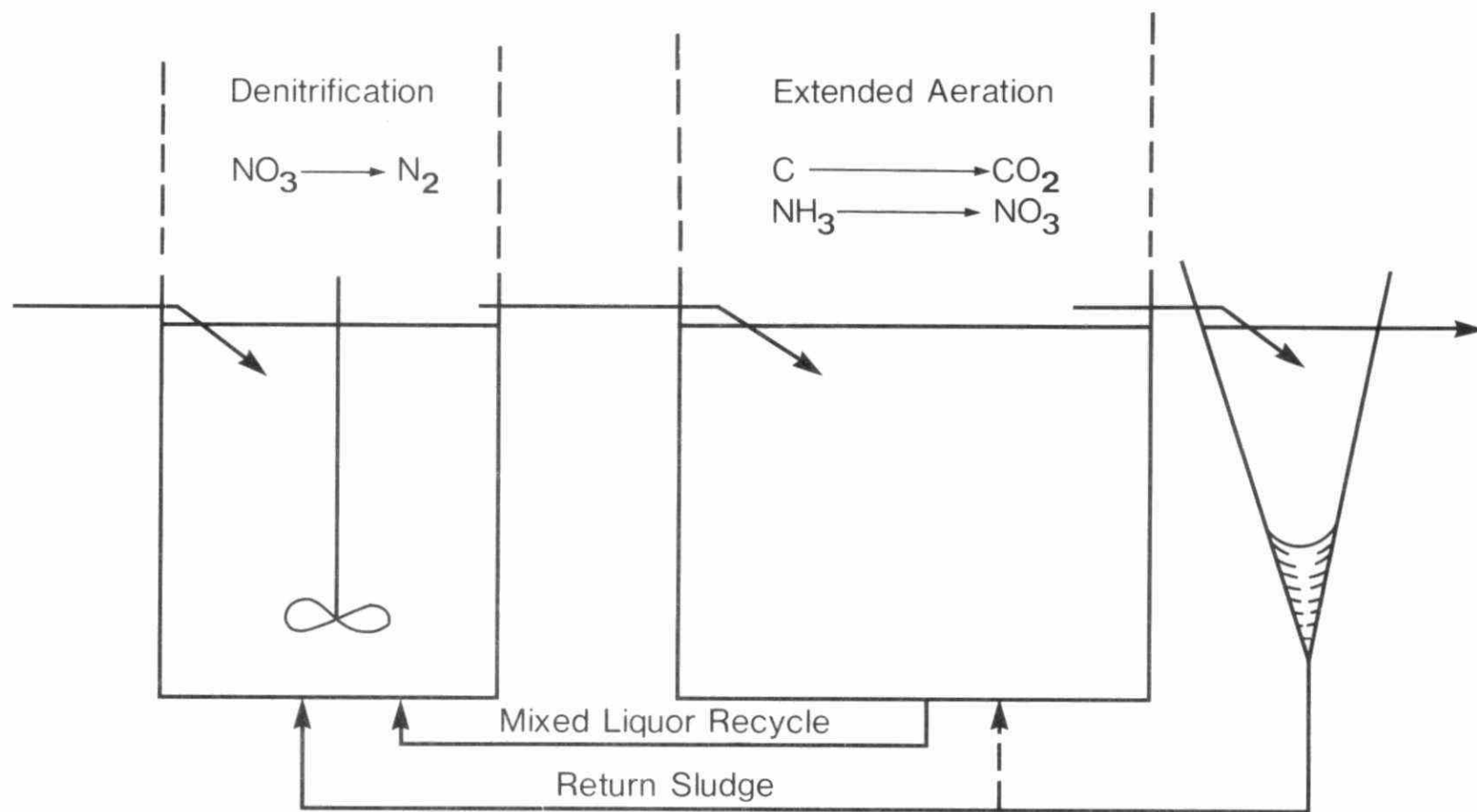


Figure 1. Du Pont of Canada Process

2. LITERATURE REVIEW

2.1 Nitrogen Content of Sewage

Domestic sewage contains nitrogen compounds in concentrations that can range from near zero to 100 mg/l. In most cases, however, the total nitrogen content of sewage is 20-40 mg/l (2). The nitrogen is present as ammonia and various organic nitrogen compounds. In conventional sewage treatment a portion of these nitrogen compounds are removed by primary clarification and by cell synthesis in activated sludge units. Nitrogen removal in conventional activated sludge plants with normal loadings ranges from 30-50% (13).

2.2 Alternate Methods of Nitrogen Removal

During the past ten years a great deal of research has been concentrated on removing nitrogen from sewage because of its role in eutrophication (14, 16, 25) and because of the nitrogenous oxygen demand it exerts on receiving waters. Many processes have been studied and the main ones include: air stripping of ammonia (11), ion exchange (9, 10), reverse osmosis (20), breakpoint chlorination (5), and biological nitrification and denitrification.

Air stripping and biological denitrification have a significant cost advantage over the other three methods (17) but air stripping is not suitable in Canada because of very low efficiency at ambient temperatures less than 32°F. For these reasons biological treatment has become the preferred treatment.

2.3 Denitrification

Biological denitrification (29,13) is a process in which bacteria reduce nitrate to nitrite, and nitrite to nitrogen gas which is given off to the atmosphere.

The process of biological denitrification has been known for over forty years because of the problem of rising (i.e. non-settling) activated sludge in secondary clarifiers (18, 22). If nitrate is present in the effluent from activated sludge units, denitrification

of nitrate to nitrogen gas can take place in anaerobic zones in the bottom of the clarifier. The nitrogen gas liberated is trapped by the sludge floc and causes it to rise to the surface.

In order for denitrification to take place, two main conditions must be satisfied. First, denitrifying bacteria must have an electron donor and, for practical purposes, this means a source of bio-degradable organic carbon. The second requirement is that bacteria must have an anaerobic environment (23) for denitrification to be initiated. There has been considerable debate on the role of oxygen in inhibiting denitrification with many conflicting results (28), but in general denitrification is only initiated in the absence of oxygen. It has been reported in the literature (26) that once denitrification is established under anaerobic conditions it continues at low but measurable rate with dissolved oxygen concentrations well above 0.5 mg/l.

Painter (21) in his literature review of inorganic nitrogen metabolism in microorganisms, discusses the role of dissolved oxygen in suppressing denitrification: "It is well established that most denitrifying enzyme systems have first to be induced by growth of the organism in the presence of nitrate and absence of oxygen". He further states: "If the dissimilatory system (denitrification) is present, oxygen will at least partially repress further enzyme synthesis but will not cause its disappearance".

Painter lists a number of papers in which the authors report denitrification under aerobic conditions although he casts some doubt on them, because dissolved oxygen measurements were not made. The tests were generally carried out in Warburg type apparatus in which the bacteria were shaken along with air or various oxygen-nitrogen mixtures. In one of these studies by Wuhrmann (28), six denitrifying bacteria were studied for their ability to reduce nitrite in air. All strains but one reduced nitrite in air, four were inhibited to the extent of about 50 per cent of the rate in nitrogen while the sixth, a spirillum, reduced nitrite at the same rate in air as in nitrogen.

On this work Painter comments: "The method of aeration - air bubbling, vessel on shaking machine - probably insured positive concentrations of dissolved oxygen in the liquid. It was shown that nitrite was not assimilated in these experiments."

Fewson and Nicholas (12) studied quantitatively the effect of oxygen on nitrate-reducing enzyme systems in cell homogenates of P. aeruginosa. Activity of shake cultures dispersed with air was about one-third of those measured anaerobically; even with 100 per cent oxygen, about 7 per cent activity was produced. Once again no dissolved oxygen measurements were made.

In batch culture studies by Wheatland and Barrett (26), nitrate reduction to nitrite was measured after 48 hours, as a percentage of the reduction observed under anaerobic conditions, at different dissolved oxygen levels from 0 to 3.5 mg/l. The plot of the data taken from that paper is shown as Figure 2.

It is apparent from these data that denitrification, initiated under anaerobic conditions, continues at a reduced rate under aerobic conditions. The curve in Figure 2 indicates a 10 to 15% residual denitrification rate at dissolved oxygen values greater than 1 mg/l.

A number of flow schemes have been tested to remove nitrogen in sewage including both suspended growth denitrification reactors (19) and anaerobic filters (24). A common element of these flow sheets is that they involve aerobic BOD reduction as a first stage, followed by nitrification of ammonia to nitrate as a second stage, and finally anaerobic denitrification as the last step. In some cases, the BOD removal and nitrification are combined into a single stage, and the individual stages may or may not be isolated by clarifiers. The preferred flow sheet to evolve from research is a three-stage activated sludge system described by Barth (3) and Mulbarger (19) and shown in Figure 3. Total nitrogen removal averaged 80% in the study by Mulbarger with an effluent total nitrogen of 6 mg/l. Methanol consumptions for the process ranged from 3 to 4 lb of methanol per lb of N.

Assuming an average NO_3^- - N concentration of 15 mg/l in the

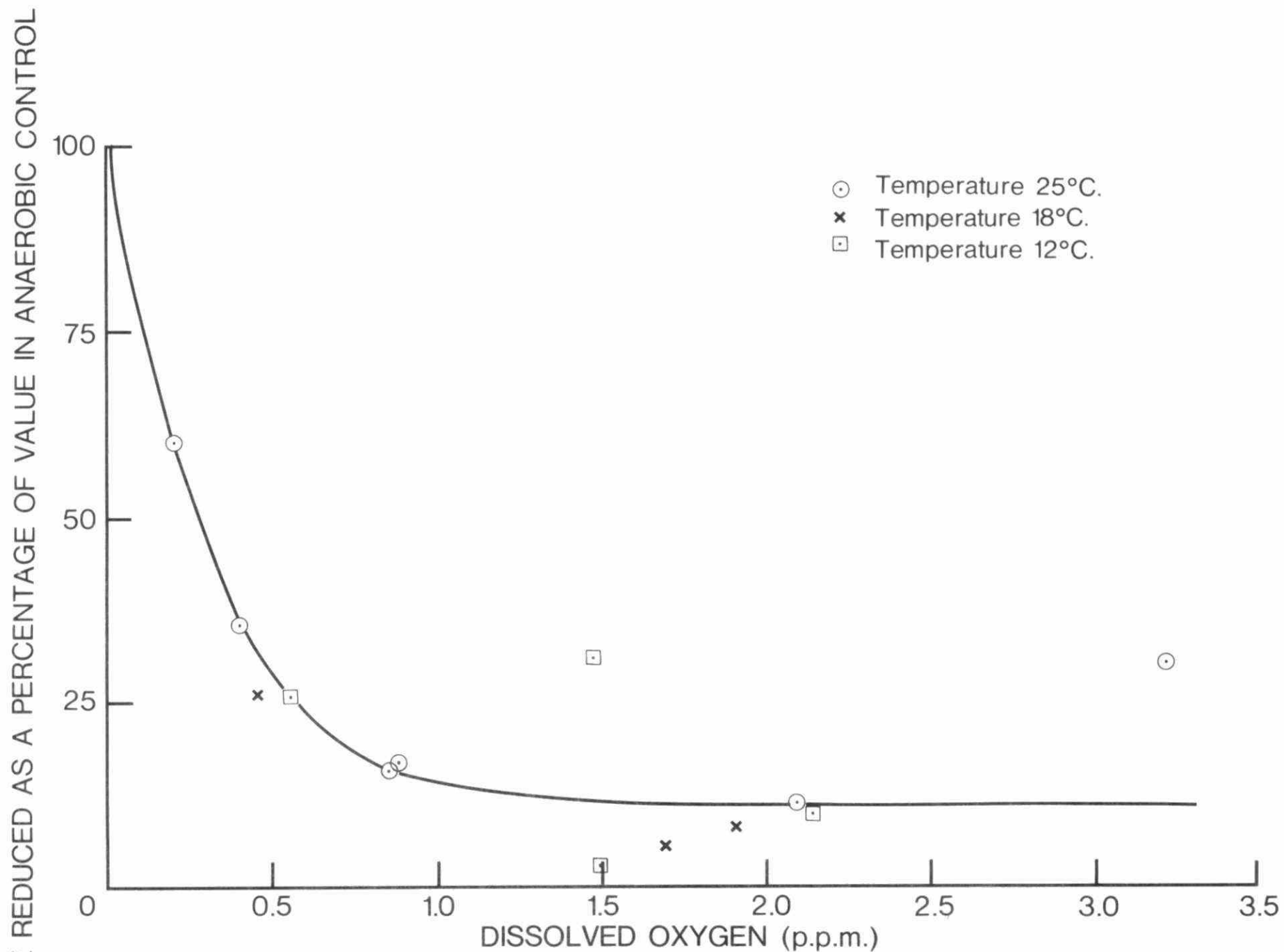


Figure 2. Nitrate Reduced in 48 Hours in Aerobic Cultures as a Percentage of That in Anaerobic Cultures (26).

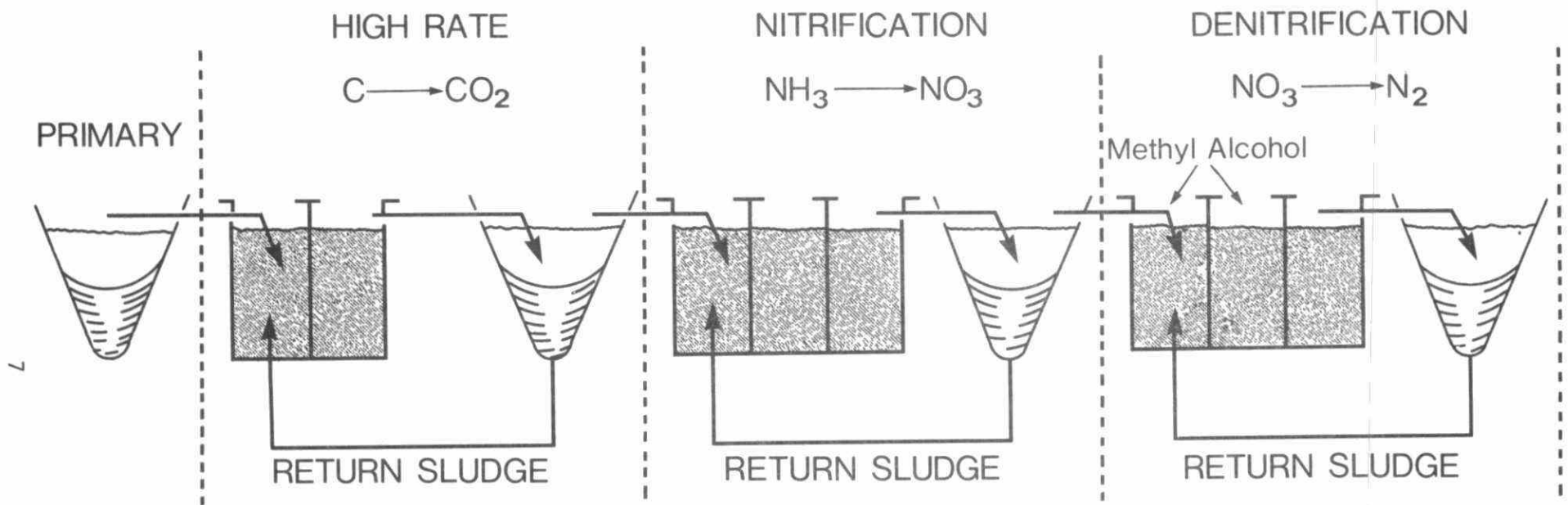


Figure 3. Three Sludge Systems for Nitrogen Removal Barth(3) and Mulbarger(19)

feed to the denitrification stage, a methanol cost of 3.2¢/lb* (25 1/2¢ Imp G) (4) and a methanol consumption of 3.5 lb/lb N, the cost of nitrogen removal for methanol alone is about 2¢/1,000 gal.

There are a number of alternatives to methanol being studied, which would reduce the cost of the electron donor. However, even if the cost of the organic approaches zero by using waste materials, the additional investment and operating cost for transportation and storage of this material will remain a significant cost factor in nitrogen removal.

If successful, the process being tested would eliminate the methanol cost by using influent sewage as electron donor for denitrification, and would reduce investment in the process by simplifying the flowsheet required. There are additional potential savings in aeration and sludge handling cost because a fraction of the influent BOD is removed by denitrification and the overall sludge production should be less than the three sludge system.

The flowsheet being tested has the denitrification stage first, followed by an extended aeration stage that achieves BOD reduction and nitrification. Mixed liquor from the aerated stage is recycled at a high rate to the anaerobic stage where nitrate is denitrified using the sewage as an organic carbon source (see Figure 1). Similar processes were studied by Ludzack and Ettinger (15) in 1962 and by Barth and Ettinger (1) in 1967. Results from these experiments were disappointingly poor and apparently no further exploration of the process has been made. The study by Ludzack and Ettinger in 1962 was carried out on bench scale apparatus in which measurement and control of mixed liquor recycle rate was impossible. The system was periodically upset by highly dissolved oxygen concentration in the first anaerobic stage and this too was caused by the equipment configuration.

In the later study by Barth and Ettinger very little detail of the study is reported, however, it appears that the test was of short duration and no attempt was made to optimize performance by varying residence time or recycle rate.

* Methanol cost has recently increased sharply and it is likely that long term prices will be 10¢/lb or higher.

3. EQUIPMENT AND METHODS

3.1 Existing Equipment

The package treatment plant used for this study is manufactured by Aero-O-Floc Corporation, Florence, Kentucky. It is an extended aeration system designed with 24 hours residence time to treat 60,000 U.S. gallons per day of sewage at a BOD of 200 mg/l. Aeration and mixing are provided by diffused air. The unit is equipped with two 10 hp blowers and these are operated one at a time on an intermittent basis. The clarifier section consists of two hoppers, each equipped with air lift sludge return and surface skimming. The overflow weir is protected by a surface baffle to retain floating sludge. The design clarifier overflow rate is 170 U.S. gal/day/ft² of total surface area.

Performance data were collected before the experimental modifications by taking a series of grab samples of raw sewage, aeration tank contents and treated effluent. Beginning 8th of November, effluent samples were 24 hour composites pumped at a constant rate from the chlorination chamber. The results are shown in Table 1 and indicate that nitrification is fairly complete with only 1-2 mg/l TKN in the effluent.

Most of the raw sewage analyses shown in Table 1 were completed on grab samples taken during the day. The nitrogen-in-effluent figures indicate high nitrogen removal was already taking place. This large discrepancy was explained when 24 hour composite samples were taken of the raw sewage from an automatic sampler. The composite results were considerably lower because the sewage entering the plant on the 4-12 and 12-8 shift was practically pure water. A number of water sources were discovered but could not be eliminated without further large expenditures.

3.2 Equipment Modifications

The flow diagrams in Figures 4 and 5 show the process and modifications to the existing plant.

The raw sewage was passed through the comminutor to the denitrification (DN) tank. Nitrified recycle from the extended aeration tank

TABLE 1. PERFORMANCE DATA CONVENTIONAL OPERATION

					RAW SEWAGE**				AERATION TANK (FILTERED)				EFFLUENT (FILTERED)				REMARKS
DATE	TIME	AERATION TANK		SEWAGE FLOW USGPM	TKN	NO ₃	NO ₂	TOC	TKN	NO ₃	NO ₂	TOC	TKN	NO ₃	NO ₂	TOC	
		TEMP. °C	pH														
All results expressed as mg/l of N or C.																	
11/10/72	0900			34	34	0.3	0.7	43	2	3.3	0.07	10	1	4.0	0.03	7	D.O. 4-5 mg/l
	1200	16		38	26	0	0.5	48	4	4.8	0.07	8	2	3.8	0.03	8	
	1500	16		30	24	0	0.6	25	6	5.4	0.07	12	1	5.4	0.03	9	
13/10/72	0830	13		30	18	0	0.6	39	1	4.7	0.07	10	1	4.5	0.03	9	
	1030	13		36	30	0.2	0.6	25	2	5.0	0.14	8	1	4.4	0.03	7	
	1230	14		54	20	0.2	0.5	25	2	5.0	0.14	9	1	4.4	0.03	8	
	1530	15		40	35	0.5	0.8	39	2	6.3	0.07	16	2	6.1	0.03	13	
25/10/72	0830	16		40 Ave.	22 24.1	0.3 0.2	0.6 0.6	56 39.6	1 2.2	3.5 4.7	0.03 0.07	13 9.2	1 1.3	4.2 4.6	0.01 0.03	7 8.3	Air on con- tinuous
	1230	16		40	21	0.4	0.4	32	1	5.4	0.03	8	1	3.4	0.03	8	D.O. 7-8 mg/l Add Floc- culant
	1530	16		44	11	0.2	0.6	22	1	3.6	0.05	8	1	5.3	0.04	7	
30/10/72	1245	17		40	31	0.8	0.6	35	1.5	5.4	0.05	14	12*	4.4	0.05	14	
1/11/72	0830	16		34	13	0.5	0.6	28	7	6.5	0.14	9	4*	5.9	0.05	9	
4/11/72	0830	16		36	13	0.4	0.5	15	7	5.1	0.10	10	5*	5.1	0.05	7	
8/11/72	0900	17	7.2	40	12	0.9	0.5	21	9	5.0	0.41	16	7*	5.5	0.03	8	Effluent samples are continuous 24 hr. compo- sites from this date on.
13/11/72	0900	16	7.4	40	9.3	0.4	0.4	23	1.4	1.7	0.20	8	0.1	3.4	0.03	9	
22/11/72	0900	14	7.3	30	25	0.4	0.6	20	3	5.2	0.10	9	3	6.1	0.03	9	

TABLE 1 (CONT'D)

					RAW SEWAGE**				AERATION TANK (FILTERED)				EFFLUENT (FILTERED)				REMARKS
DATE	TIME	AERATION TANK		SEWAGE FLOW USGPM	TKN	NO ₃	NO ₂	TOC	TKN	NO ₃	NO ₂	TOC	TKN	NO ₃	NO ₂	TOC	
		TEMP. °C	pH														
25/11/72	0815	13	7.1	28	8	0.2	0.7	17	1	4.5	0.1	10	1	5.3	0.03	10	
7/12/72	1200	13	6.9	40	20	0.6	0.5	29	3	7.7	0.1	17	1	2.7	0.02	13	
13/12/72	1200	14	6.9	36 Ave.	16.5	0.5	0.6	30 27.2	5.8	5.1	0.15	11.6	-	4.8	0.04	9.9	BOD 68 mg/l in Raw Sewage
28/1/73	24 hr. comp.	10	6.9	34	5.8	0.3	0.6	12	3.9	2.6	<0.1	11	1.8	3.9	<0.1	9	
5/2/73	24 hr. comp.	11	7.2	40	5.6	0.2	0.8	17	-	2.6	<0.1	8	-	2.6	<0.1	7	
9-12/2/73	72 hr.			34	8.0	0.1	0.4	16	0.1	4.2	<0.1	9	0.1	5.4	<0.1	9	
									GRAB SAMPLES								

* Possible Analytical Problem But Not Confirmed.

** TKN on UNFILTERED SEWAGE; NO₃, NO₂, TOC on FILTERED SAMPLE.

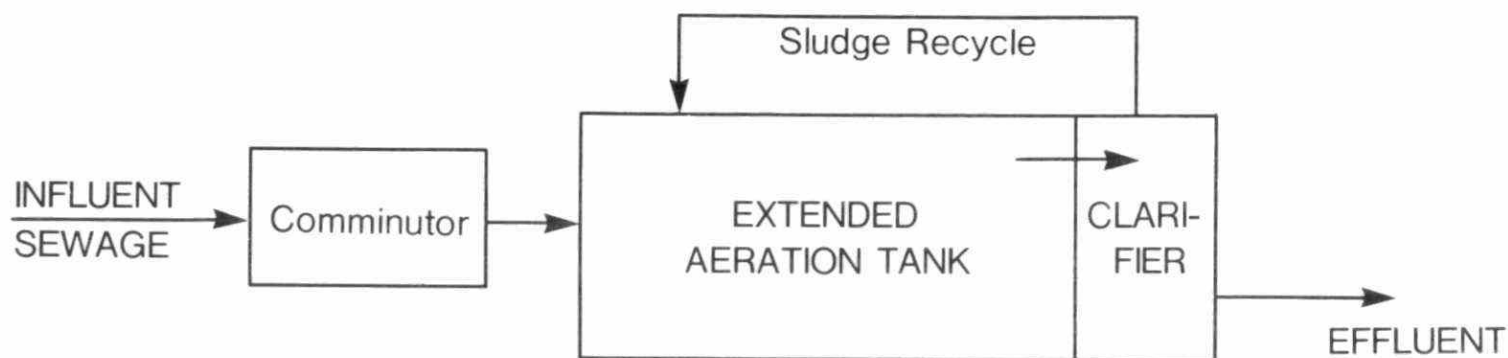


Figure 4. Existing Treatment Plant

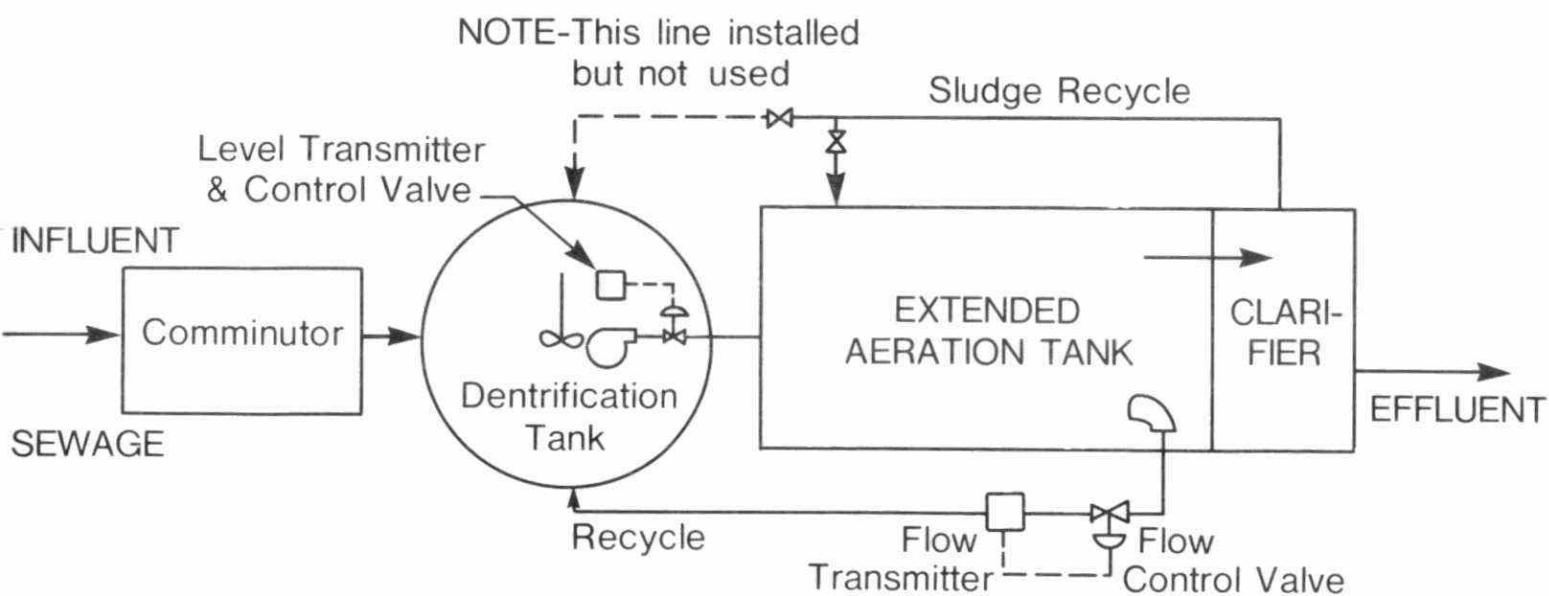


Figure 5. Modified Treatment for 'N' Removal
(Including Modifications for Automatic Control)

was pumped into the DN tank at a rate from 0.5 to 4 times the raw sewage flow and the DN tank effluent was pumped back to the aeration tank on level control. This allowed bacteria to utilize the raw sewage as an electron donor for denitrification. Return sludge from the clarifier was returned to the aeration tank by existing air lift pumps.

3.3 Start-Up Problems

The process was started up in December, 1972 in the following sequence. The recycle pump was started up and the flow was set with a manual gate valve at 70 gpm. This flow was measured and recorded. Next, the DN tank pump and mixer were started up. The DN tank level was controlled by an on-off switch on the pump operated by a float mechanism. Some problems resulted from the float sticking in the on or off position. The main problem, however, was caused by plugging in the recycle line manual valve causing a steadily declining flow. This required frequent opening of the valve to clear followed by re-adjustment. Continuous 24 hour surveillance of the system could not be provided and therefore the system was impractical. It was decided to make modifications to the installation to correct these problems before carrying out any further testing. Manual flow control on the recycle pump was replaced with automatic control. A 3" annin valve was installed along with a pneumatic controller which was connected to the existing flow transmitter. The DN tank level was converted to proportional control in place of the on-off system. A level controller operated a 4" annin valve at the discharge of the DN tank pump. A larger impeller was installed in the DN tank pump. These changes provided stable and reliable operation for the experiments and gave pumping capacity to maintain up to 100 gpm recycle.

3.4 Sampling and Analytical Techniques

Raw sewage and effluent analyses were carried out on composite samples taken over a 24 hour period by automatic samplers. The DN tank and aeration tank analyses were done on grab samples taken between 8 and 9 A.M.

The aeration tank and effluent composite sample results did not differ greatly because of the averaging effect of the 24 hour aeration time. The effluent tended to be a few mg/l lower in nitrate nitrogen than

the aeration tank. It is believed that low levels of bacteria in the effluent composite were causing denitrification and subsequent loss of nitrogen during the 24 hour collection period. For this reason the aeration tank results were used in the discussion even though they gave slightly lower nitrogen removal efficiency.

Analytical techniques for NO_3 , NO_2 and TKN were based on Standard Methods for the Examination of Water and Waste Water, 12th edition. All samples were filtered before analysis through Whatman #1 paper except for TKN analysis on raw sewage.

4. RESULTS AND DISCUSSION

4.1 Process Performance

Following installation of automatic flow and level controls, the system was started up with the recycle flow at 70 gpm, just over twice the raw sewage flow. The DN tank level was set at 50% (12,000 gal) or a residence time of six hours. Test operating conditions are shown in Table 2 and analytical results are shown in Table 3.

With the weak sewage and high dissolved oxygen in the aeration tank (7-8 mg/l), the dissolved oxygen in the denitrification (DN) tank would not go below 1.0 mg/l. The recycle flow was reduced to equal the sewage flow in order to reduce the dissolved oxygen input to the DN tank.

The dissolved oxygen level decreased to about 0.5 mg/l * but there was no apparent denitrification. The influent and effluent total nitrogen levels are shown in Figure 6. From the February 5th start-up until February 16 little or no denitrification was observed. Nitrogen and BOD loadings in raw sewage were too low for any meaningful test. On February 17th the addition of hexamethylene diamine was begun to increase the carbon and nitrogen load in the raw sewage. Hexamethylene diamine (HMD) was chosen because it is biodegradable, it contains combined organic nitrogen and it is manufactured in large quantities on the plant site. The HMD was pumped into the sewer system continuously using a Lapp metering pump via a washroom sink adjacent to the laboratory. Late in the test an HMD - methanol mixture was used to attain higher BOD without increasing the nitrogen load. Methanol was selected because it was readily available on site and it is completely miscible with HMD solution, making the addition easier.

The amounts were controlled to give a TKN in sewage of 25 to 35 mg/l and BOD over 100 mg/l.

The total nitrogen in aeration tank (filtered sample), as shown in Figure 6, reached a maximum of 11 mg/l on February 23rd with a TKN in feed of about 30 mg/l. The effluent total nitrogen, which was mainly

* Note: D.O below 1.0 mg/l. may not be significant.

TABLE 2. TEST OPERATING CONDITIONS

Date	Ave. Flow GPM		Temperature °C			Dissolved O ₂ mg/l			pH				DN * Tank Level %	Remarks
	Re- cycle	Sew- age	Amb- ient	DN Tank	Aer. Tank	DN Tank	Aer. Tank	Effl.	Sew- age	DN Tank	Aer. Tank	Effl.		
5/2/73	70	30	0	11	11								50	Start up
6/2/73	70	35	-2	11	12								50	system at
7/2/73	70	30	3	12	12	1.0							50	2:1 recycle
8/2/73	40	32	-2	11	12	0.4	8.0	6.8					100	Reduced recycle
9/2/73	40	40	-15	12	15	0.8	9.0	7.0					65	to 1:1
12/2/73	40	34	-8	Line frozen	11.5	0.4	8.5	7.0					100	DN line Frozen (thawed and repaired)
13/2/73	40	42	-12	11.5	11.5		8.6	7.8					50	
14/2/73	40	32	-8	11.5	11.5	0.5	8.9	7.9					80	
16/2/73	40	32	-16	11.5	11.0								50	
17/2/73	40	34	-22	12.0	11.0		8.9	7.8					50	Begin HMD feed 8 ml/min
18/2/73	40	28	-19	12.5	11	<1	8.9	7.6					50	
19/2/73	40	30	-3	12.5	12.5	<1	7.7	6.4					50	
20/2/73	40	27	+3	11.5	0.5	6.2	6.0						53	HMD feed 16 ml/min

Clarifier Sludge Recycled to Aeration Tank at 20-25 GPM (Approx.)

* 0% Level = 3,700 USG

100% Level = 19,600 USG

NOTE: All temperature's taken at 0900 to 1000 hours each day. Flows reported in USGPM.

TABLE 2 (cont'd)

Date	Flow GPM		Temperature °C			Dissolved O ₂ mg/l			pH				DN Tank Level %	Remarks
	Re- cycle	Sew- age	Amb- ient	DN Tank	Aer. Tank	DN Tank	Aer. Tank	Effl.	Sew- age	DN Tank	Aer. Tank	Effl.		
21/2/73	40	29	-3	12	12.5	0.1	5.8	6.0					51	
22/2/73	40	30	-2	11.0	12.0	0.3	6.0	5.6					70	
23/2/73														
26/2/73	40	25	-10	12.0	11.0	0.2	3.0	2.5					75	
27/2/73	40	29	-16	11.0	12.0	0.2	4.0	3.5					75	
28/2/73	40	40	-14	11.5	11.0	0.1	3.7	3.4					75	
1/3/73	40	27	-6	12	12	0.1	1.4	2.2	9.0	7.6	7.6	7.3	75	HMD 20 ml/min
2/3/73	65	25	-2	12	13	0.2	2.5	2.2	8.7	7.0	6.8	6.8	80	HMD 16 ml/min
5/3/73	40	38	0	11	10	0.3	5.0	4.4	7.8	7.2	7.1	7.3	80	HMD-MeOH 75:25 @ 20 ml/min
6/3/73	40	39	2	10	11	0.2	4.2	5.0	8.7	6.9	6.8	6.8	80	
6/3/73														
7/3/73	40	41	4	10	11	0.3	4.4	3.8	8.4	7.0	7.0	6.9	80	HMD-MeOH 50:50 @ 28 ml/min
9/3/73	40	43	5	10	11	0.3	4.4	3.4	8.4	7.4	7.3	6.8	88	
10/3/73	40	34	4	10	11	0.2	3.5	3.0	8.3	7.1	7.0	6.9	88	HMD-MeOH 30 ml/min
11/3/73	40	35	6	10	11	0.3	4.0	3.5	8.4	7.2	7.0	7.0	$\frac{100}{85}$	Tank Level at 100% in morning Corrected to 85%

TABLE 2 (cont'd)

Date	Flow GPM		Temperature °C			Dissolved O ₂ mg/l			pH				DN Tank Level %	Remarks
	Re- cycle	Sew- age	Amb- ient	DN Tank	Aer. Tank	DN Tank	Aer. Tank	Effl.	Sew- age	DN Tank	Aer. Tank	Effl.		
12/3	40	37	10	10	12	0.2	3.2	2.8	7.4	7.5	7.0	7.2	88	
13/3	40	40	4	10	12	0.2	3.0	2.7	8.4	7.4	7.0	7.1	88	
14/3	40	40	3	10.5	12	0.2	4.8	3.5	8.3	7.3	7.0	7.0	88	
15/3	40	42	10	10	12	0.3	3.3	2.3	8.1	7.3	6.9	6.9	88	
20/3	45	36	-3	11	11.5	0.1	2.1	1.6	8.0	7.5	7.2	7.1	88	
21/3	45	40	-1	10.5	11.5	0.1	1.0	0.5	8.4	7.6	7.0	6.9	88	Put 2nd aerator on
22/3	50	32	0	10	12	0.4	3.9	2.5	8.4	7.4	6.9	6.9	100	

TABLE 3. ANALYTICAL RESULTS

Date	Sewage mg/l			DN Tank mg/l					Aeration Tank mg/l				Remarks
	NO ₃ -N +NO ₂	UNFILT -ERED TKN	TOC	NO ₃ -N	NO ₂ -N	TKN	TOC	SS VSS	NO ₃ +NO ₂	TKN	TOC	SS VSS	
5/2/73	1.0	5.6	17	2.7	0	3.0	9	<u>5450</u> 3130	2.7	2.5	8	<u>5040</u> 2910	Start up
6/2/73				2.4	0.3		16		*3.5				system at
7/2/73				3.0	0.3		19		*4.0				2:1 recycle
8/2/73				2.0	0.1		10		*3.8				Reduced recycle
9/2/73			34	2.0	0.2		25		*3.5				to 1:1
12/2/73	0.5	8.0	16	3.4	0	0.3	9	<u>4670</u> 2750	*4.2	<0.1	9	<u>4780</u> 2860	DN line frozen (thawed and repaired)
13/2/73			14	3.1	0.3				*6.0				
14/2/73													
16/2/73													
17/2/73			20				16				15		Begin HMD feed
18/2/73	0.8	5.6	24	6.1	0	5.6	22		6.5	<0.1	13		8 ml/min
19/2/73			25				19				13		
20/2/73	0.5	13.1	38	4.8	0.2	1.8	18	<u>2760</u> 1710	8.2	0.7	16	<u>5420</u> 3230	HMD feed 16 ml/min
21/2/73	0.5		55	5.3	0.2		26		7.4		12		

* Effluent analysis instead of Aeration Tank

** BOD instead of TOC

TABLE 3 (cont'd)

Date	Sewage mg/l			DN Tank mg/l					Aeration Tank mg/l				Remarks
	NO ₃ -N +NO ₂	TKN	TOC	NO ₃ -N	NO ₂ -N	TKN	TOC	SS VSS	NO ₃ +NO ₂	TKN	TOC	SS VSS	
22/2/73	0.6		<u>56</u> **134	3.5	1.1		<u>30</u> **44		10.9		<u>19</u> **4		
23/2/73				2.5				<u>3250</u> 2100	11.6			<u>5560</u> 3780	
26/2/73	0.6	32.5	74	0.6	4.1	15.4	37		10.5	<0.1	16		
27/2/73	0.5		74	1.3	3.6		32		10.3		27		
28/2	0.4	25.8	45	1.1	2.3	8.1	23		9.0	<0.1	15		
1/3/73	0.7		70	1.0	4.3		27		8.6		14		HMD 20 ml/min
2/3/73	0.5	27.4	56	2.2	4.4	8.4	17	<u>3570</u> 2060	11.5	<0.1	14	<u>5040</u> 3980	HMD 16 ml/min
5/3/73	0.3		40	0.7	2.4		26		7.5		20		HMD-MeOH 75:25 20 ml/min
6/3/73	0.4	28.0	53	2.3	1.9	6.7	24		7.0	<0.1	12		
6/3/73				0.7	2.4								
7/3/73	0.4		<u>42</u> **73	2.3	1.4		<u>18</u> **19	<u>2500</u> 1650	7.7		<u>11</u> **1	<u>5600</u> 3550	HMD-MeOH 50:50 28 ml/min
9/3/73			47				23				11		
9/3/73													
10/3/73	0.4	27.2	63	0.2	2.6	8.7	35	<u>2340</u> 1570	4.1	<0.1	12	<u>5040</u> 3250	HMD-MeOH @ 30 ml/min
11/3/73	0.5		58	0.2	2.3		24		3.6		9		
12/3/73	0.9	36.2	117	0	1.8	8.4	52		3.9	<0.1	40		
13/3/73	0.3		55	0	1.6		24		5.1		7		

TABLE 3 (cont'd)

Date	Sewage mg/l.			DN Tank mg/l.					Aeration Tank (effluent) mg/l.				Remarks
	NO ₃ -N +NO ₂	TKN	TOC	NO ₃ -N	NO ₂ -N	TKN	TOC	SS VSS	NO ₃ +NO ₂	TKN	TOC	SS VSS	
14/3/73	0.3	29.8	50	0	0.8	11.1	10		2.8	2.2	7		Effluent SS 8 mg/l, VSS 8 mg/l
15/3/73	0.3		50	0	1.0		26	<u>2300</u> 1570	5.1		9	<u>5500</u> 3660	
20/3/73	0.4		38	0	0		16		2.5		11		
21/3/73	0.3		50	0	0		23		3.6		11		
22/3/73	0.3	31.2	52	0	0	8.4	22		3.9	0.1	8		
23/3/73	0.2	25.0	49	0	0		25	<u>3220</u> 2228	2.8	0.1	7	<u>5460</u> 3660	
**BOD													
NOTE	Raw Sewage composite had low suspended solids because of low loading and were not measured.												

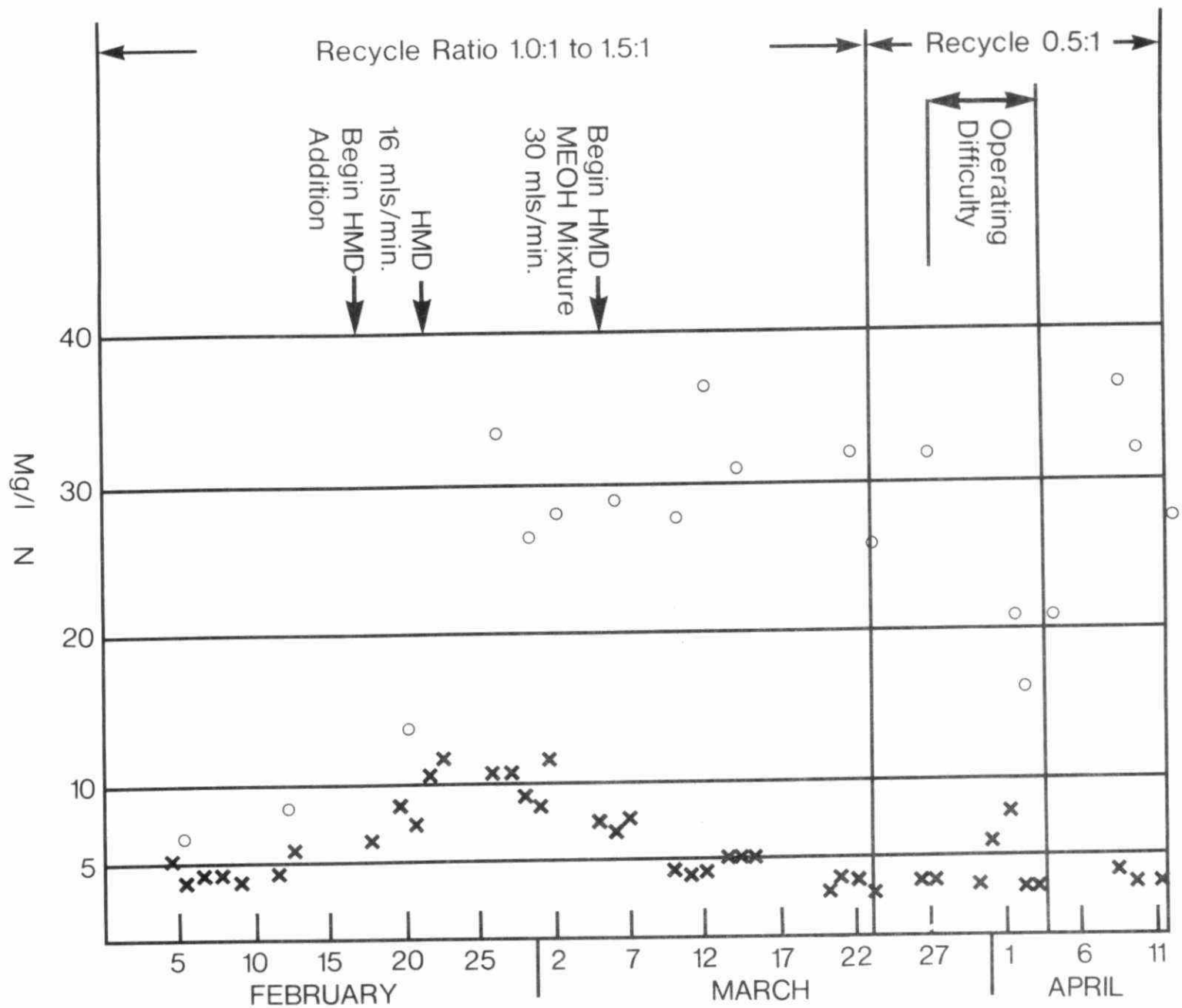


Figure 6. Process Performance

nitrate, declined steadily until it dropped below 5 mg/l by March 10th and remained there until the recycle ratio was reduced to 0.5:1 on March 23rd. The average nitrogen removal (filtered effluent) was 87% based on an average aeration tank total filtered nitrogen level of 3.9 mg/l for the period from March 10 to 23rd. During the period of March 10th to 23rd, the temperature of the DN tank was between 10 and 12°C. The efficiency of nitrogen removal was in excess of 85% during this period,

During the start-up and the initial period of HMD addition little or no denitrification took place in the stirred tank as can be seen from analytical results of February 20th in Table 3. The $\text{NO}_3^- + \text{NO}_2^-$ nitrogen in the aerated tank was 8.9 mg/l, and the $\text{NO}_3^- + \text{NO}_2^-$ nitrogen in the anaerobic tank was 5.0. With an average recycle ratio of 1.4 to 1 for February 19th - 20th the predicted DN tank $\text{NO}_3^- + \text{NO}_2^-$ nitrogen with zero denitrification would be 6.2 mg/l indicating a low level of denitrification. This was followed by a transition period during which the DN tank nitrate value decreased to approximately 1 mg/l and residual nitrite values of about 4 mg/l appeared.

This partial denitrification may have been due to residual dissolved oxygen (D.O.) of up to 0.4 mg/l inhibiting denitrification. It may also have been the result of acclimation of bacteria to hexamethylene diamine. The residual D.O. readings remained at 0.1 to 0.4 mg/l and the NO_3 plus NO_2 in the DN tank steadily declined and reached zero by March 20th.

It was impossible to carry out a complete nitrogen balance with the type of equipment used in this experiment and the number of analyses are too few to claim accuracy for this nitrogen balance. However, a brief look at the nitrogen balance in the stages on March 22nd, a typical day when the system was relatively stable, indicates a substantial portion of the nitrogen was being removed by some mechanism other than by denitrification in the anaerobic tank.

Approximate Nitrogen Balance - March 22nd

Total Sewage Fed in 24 hours		382,464	lb
Total N fed in 24 hours	$\frac{382,464 \times 31.5 \text{ mg/l}}{10^6}$	=	12.0 lb
Total N in Filtered Effluent	$\frac{382,464 \times 3.9 \text{ mg/l}}{10^6}$	=	1.49 lb
Total Recycle of Aeration Tank Mixed Liquor		579,600	lb
Total N Removed by recycle to DN Tank	$\frac{579,600 \times 3.9 \text{ mg/l}}{10^6}$	=	2.25 lb

Of the total N fed only 18% of it was removed by recycle of NO_3^- N from the aeration tank to the DN tank. Of the 31.5 mg/l N in feed, this represents 5.4 mg/l.

The existence of some "other" mechanism for nitrogen removal was confirmed by reducing the recycle ratio to approximately 0.5:1 and later by eliminating the anaerobic stage altogether. The data for this period of operation are shown in Tables 4 and 5. Following some initial mechanical difficulties at 0.5:1 recycle from March 27th to April 3rd, the system was brought to steady state conditions. The analyses on April 9th, 10th and 12th show the nitrogen removal almost unaffected by the drop in recycle ratio. Aeration tank filtered nitrogen remained below 5 mg/l confirming the presence of nitrogen removal by some unknown mechanism.

When the DN tank and recycle were eliminated from the system, the effluent nitrogen went up to 9-12 mg/l. This is close to the total one would get by adding the 5-6 mg/l removed by recycle to the 3-5 mg/l of nitrogen present in effluent during the period of 87% nitrogen removal.

4.2 Possible Explanation of High Nitrogen Removal

A sludge balance between February 20th and March 23rd, using the data in Table 4, shows a solids accumulation in the system of 11 lb/day of VSS (difference between total lb VSS Feb. 20 and Mar. 23). In addition

TABLE 4
ANALYTICAL RESULTS AT LOW AND ZERO RECYCLE

Date	Sewage mg/l			DN Tank					Aeration Tank				Remarks
	NO ₃ -N +NO ₂	Unfiltered TKN	TOC	NO ₃ -N	NO ₂ -N	TKN	TOC	SS VSS	NO ₃ -N +NO ₂	TKN	TOC	SS VSS	
26/3/73	0.3		63	TR	0.3		43		3.3		17		Recycle Ratio 0.5:1
27/3/73	0.2	31.2	68	TR	TR	10.6	33		1.9	1.4	6		
28/3/73													
30/3/73	0.2		36	TR	2.0		23		2.8		9		
31/3/73	0.2		50	TR	2.2		18	2220 1520	5.2		13	5600 3800	Synthetic Feed intermittent
1/4/73	0.2	20.1	54	TR	0.5	6.4	28		3.1	4.2	14		
2/4/73	0.2	15.3	52	TR	0.5	7.5	30		2.3	0.1	12		
3/4/73	0.7		32	0.4	1.5		39		2.5		12		
4/4/73		20.6	60				40	2000 1470		0.1	26	5310 3750	
5/4/73													- Aeration tank unfiltered TKN 376 mg/l. This is 10% on VSS.
9/4/73	0.2	36.7	68	TR	1.9	11.3	33		4.5	0.1	17		
10/4/73	0.3	31.5	63	TR	1.9	9.2	26		3.1	TR	16		
11/4/73													
12/4/73	0.2	26.2	65	TR	1.7	9.5	27	1950 1500	3.0	TR	10	5600 4030	
13/4/73													DNTK S/D zero recycle
16/4/73	TR								5.7	2.8	9	5410 4780	
17/4/73	0.1								4.4				
18/4/73	0.2	27.3	23						8.8	TR			

TABLE 4 (cont'd)

Date	Sewage mg/l			DN Tank					Aeration Tank				Remarks
	NO ³ -N +NO ₂	TKN	TOC	FILTERED					FILTERED				
				NO ₃ -N	NO ₂ -N	TKN	TOC	SS VSS	NO ³ -N +NO ₂	TKN	TOC	SS VSS	
20/4/73	0.1	20.6	24						6.8	TR	12		
30/4/73	TR	16.7	47						5.3	0.6	7	6200 4000	
2/5/73	0.1	39.0	42						8.2	TR	12		
4/5/73	TR	40.7	55						12.1	0.3	9		
7/5/73	TR	29.4	60						9.3	TR	10		
9/5/73	TR	29.0	50						11.3	TR	12		
11/5/73	1.2	27.1	43						9.8	TR	14	6500 4560	

TR = TRACE

TABLE 5

TEST OPERATING CONDITIONS AT LOW AND ZERO RECYCLE RATIOS

Date	Ave. Flow GPM		Temperature °C			Dissolved O ₂ mg/l			pH				DN * Tank Level %	Remarks
	Re- cycle	Sew- age	Amb- ient	DN Tank	Aer. Tank	DN Tank	Aer. Tank	Effl.	Sew- age	DN Tank	Aer. Tank	Effl.		
26/3/73	15-20	28	6	11	12	0.2	0.6	0.6	8.6	7.8	6.8	6.8	88	Recycle at .5:1
27/3/73	"	32	2	11	12	0.2	1.2	1.0	8.7	7.9	7.2	7.2	88	
28/3/73	"	27	0	1	12	0.2	2.4	1.4	8.5	7.5	6.9	6.9	100	
30/3/73	"	35	8	8	11	0.3	2.0	1.0	8.4	7.8	7.0	7.2	88	
31/3/73	"	30	12	9	11	0.2	3.1	1.5	8.6	7.5	7.0	7.1	"	
1/4/73	"	27	8	8	12	0.2	2.5	1.4	8.5	7.8	6.9	7.2	"	Synthetic Feed Intermittent
2/4/73	"	33	8	8	11	0.3	2.5	1.5	8.4	7.8	7.1	7.2	"	
3/4/73	"	40	4	8	11	0.35	4.4	3.2	8.2	7.5	7.0	7.3	"	
4/4/73	"	34	5	8	11	0.3	3.5	2.0	8.4	7.8	7.2	7.3	"	
5/4/73	"	40	2	8	11	0.4	3.3	1.8	8.3	7.5	7.1	7.2	"	
9/4/73	"	30	-2	8	10	0.4	3.0	2.2	8.0	7.8	6.9	7.0	"	
10/4/73	"	30	-2	8	10	0.4	3.9	2.8	8.4	7.5	7.1	7.1	"	
11/4/73	"	30	-5	8	10	0.4	3.5	2.2					"	
12/4/73	"	32	-2	8	10	0.4	2.5	1.7	8.4	7.7	7.1	7.1	"	
13/4/73	"	30	-4	8	10	0.5	3.9	2.8					"	
16/4/73	NIL	25				S/D	1.5	1.0		S/D	7.0		S/D	S/D DN Tank (Aeration Only) Feed intermittent Apr. 20-30 because of aeration problem
17/4/73	NIL	30					0.7	0.6	8.4		7.0			
18/4/73	NIL	25					4.9	3.8	7.5		7.1	7.0		
20/4/73	NIL	28					4.9	3.8	7.3		6.9	6.9		
30/4/73	NIL	34					4.1	3.0	7.8		7.1	7.1		
2/5/73	NIL	42					3.1	2.1	7.7		7.7	7.0		
4/5/73	NIL	34					3.3	2.2	7.8		7.1	7.0		
7/5/73	NIL	30					2.5		7.8		7.0	6.9		
9/5/73	NIL	31					1.2	0.9	8.3		7.5	7.4		
11/5/73	NIL	34					1.2	0.7	8.0		7.1	7.1		

a solids level in the effluent of 10 mg/l during the period at an average flow of 35 USGPM gives an additional solids production of 4 lb/day for a total of 15 lb/day.

Analysis of the sludge for TKN on April 4th (see Table 4) indicated 10% nitrogen based on VSS and this gives a total nitrogen loss by cell synthesis of 1.5 lb of 'N' per day. This represents a consumption of 4 mg/l out of the total 30 mg/l nitrogen in feed, and accounts for 13% nitrogen removal.

An approximation of the data, assuming 150 mg/l BOD in the feed, gives a sludge yield coefficient of 0.25 lb of VSS/lb of BOD and this is a fairly typical value for extended aeration systems.

As calculated in the previous section, no more than 6 mg/l of nitrogen removal is accounted for by recycle to the first stage.

Therefore, a total nitrogen removal of 10 mg/l is accounted for by cell synthesis and recycle, leaving roughly 20 mg/l or 60% nitrogen removal unaccounted for.

The possibility of ammonia stripping from the aeration tank is unlikely, because pH generally remained between 6.8 and 7.2 and a pH of 10 to 11 is required to get any appreciable stripping.

The most probable mechanism is that denitrification, initiated in the first stage carries on in the aerobic stage, even though it is at a much lower rate. The denitrification rate required to remove 20 mg/l of N in the aerobic stage is about .005 gm N/gm VSS/day. This is 1/70th of the rate measured under anaerobic conditions at 20°C and 1/20th of the rate at 10°C (5) for waste similar to HMD. This theory of low rate aerobic denitrification is supported by the work of Wuhrmann (28), by Fewson and Nicholas (12), and by Wheatland, Barrett and Bruce (26) described in the literature review of this report.

The unusually high nitrogen removal observed in this experiment is very close to the results obtained with industrial waste at Du Pont of Canada's Maitland Works (6). The flowsheet for treating Maitland waste consisted of 36 hour anaerobic basin followed by a 5 day aerated basin followed by a clarification system. In a bench scale experiment with a recycle ratio of 1:1, the following average analyses were observed over a six week period:

FEED				ANAEROBIC STAGE			AEROBIC STAGE		
NO ₃	NO ₂	TKN	TOC mg/l	NO ₃ + NO ₂	TKN	TOC	NO ₃ + NO ₂	TKN	TOC
112	62	268	1068	0	132	457	46	20	35

Nitrogen analysis expressed as mg/l nitrogen.

TOC is total organic carbon expressed as mg/l carbon.

The anaerobic stage gave complete removal of all nitrate and nitrite in the feed. The feed concentration of reduced nitrogen was 286 mg/l and at a recycle ratio of 1:1 this should give a concentration of 143 mg/l in the anaerobic tank. The actual value of 132 mg/l is close to the predicted value and the difference could be due to physico-chemical adsorption or cell synthesis. Cell synthesis in the system was very low and the total nitrogen consumption accounted for by this mechanism was estimated at 4 mg/l N (6).

The total nitrogen in the aerated stage was 66 mg/l, showing a loss of 66 mg/l of total nitrogen from the aerated stage. The denitrification rate in the aeration tank required to remove the 66 mg/l was .0075 gm N/gm VSS/day and this is remarkably close to the .005 gm N/gm VSS/day observed in the 50,000 GPD system used in this experiment.

REFERENCES

1. Barth and Ettinger, "Managing Continuous Flow Biological Denitrification". Industrial Waste Water Conference, Proc. 7th, Austin, Tex., 1967.
2. Barth, Mulbarger, Salotto, and Ettinger, "Removal of Nitrogen by Municipal Wastewater Treatment Plants", J. WPCF, 38 12098, 1966.
3. Barth, et al, "Nitrogen Removal from Wastewaters". Environmental Protection Agency, Advanced Waste Treatment Research, Laboratory, Cincinnati, Ohio, 1970.
4. Canadian Chemical Processing, "Chemical Buyers Guide". Page 79, 1972.
5. Climenhage, "Biological Denitrification of Nylon Intermediates Waste Water". 22nd Canadian Chemical Engineering Conference, sponsored by Chemical Institute of Canada, 1972.
6. Climenhage and Stelzig, "Biological Process for Nitrogen - BOD Removal at Maitland Works, Du Pont of Canada". 20th Ontario Industrial Waste Conference, sponsored by the Ontario Ministry of the Environment, 1973.
7. Dawson and Murphy, "Factors Affecting Biological Denitrification of Wastewater". Advances in Water Pollution Research Pergamon Press N.Y. Edited by S.H. Jenkins, Page 671, 1973.
8. Dean, "Other Methods for Removing Nitrogen". Adv. Waste Treatm. and Reuse Symp., Dallas, Texas, Jan. 12-14. 1971.
9. Dean, "Removal of $\text{NH}_3\text{-N}$ by Selective Ion-exchange". Adv. Waste Treatm. and Reuse Symp., Dallas, Texas, Jan. 12-14. 1971.
10. Dobbs, "Ion Exchange for Nitrate Removal". Adv. Waste Treatm. and Reuse Symp., Dallas, Texas, Jan. 12-14, 1971.

11. Farrel, Stern, and Dean, "Nitrogen Removal from Wastewaters". U.S. Dept. Interior, Fed. WPCA, Cincinnati, Ohio, January 1968.
12. Fewson and Nicholas, "Nitrate reductase from *Pseudomonas Aeruginosa*", Biochim. Biophys. Acta 49, 335-349, 1961.
13. Johnson and Schroepfer, "Nitrogen Removal by Nitrification and Denitrification". Jour. WPCF, 36 1016-36, 1964.
14. Keeney, "The Fate of Nitrogen in Aquatic Ecosystems". University of Wisconsin Water Resources Center, Madison, 1972.
15. Ludzack and Ettinger, "Controlling Operation to Minimize Activated Sludge Effluent Nitrogen". Jour. WPCF, 34, (9), September 1962.
16. Lund, "The Ecology of Freshwater Phytoplankton". Biological Review 40:231-293., 1965.
17. Martin, "The Role of Nitrogen in the Aquatic Environment". Academy of Natural Sciences of Philadelphia, Dept. Limnology.
18. McLachlan, "The Settlement and Rising of Activated Sludge". The Surveyor, 90 34-41, 1936.
19. Mulbarger, "Modifications of the Activated Sludge Process for Nitrification and Denitrification". Federal Water Quality Administration U.S. Department of the Interior Advanced Water Treatment Research Laboratory, 1970.
20. Okey, "The Application for Membranes to Sewage Treatment". Water Res. Symp. (Ed.:Gloyne) No. 3, 327-388, 1970.
21. Painter, "A Review of Literature on Inorganic Nitrogen Metabolism in Microorganisms". Water Research, Pergamon Press. V. 4, 391-450, 1970. Water Res. Symp. (Ed.:Gloyne) No. 3, 327-388, 1970.

22. Sawyer and Bradney, "Rising of Activated Sludge in Final Settling Tanks".
Sew. Wks. J., 17 1191, 1945.
23. Skerman and MacRae, "The Influence of Oxygen on the Reduction of Nitrate
by Adapted Cells of Pseudomonas Denitrificans." Can. J. Microbiol
3215-230, 1957.
24. Smith, et al, "Nitrogen Removal from Municipal Wastewater by Columnar
Denitrification". U.S. Department of the Interior Federal Water
Quality Administration, Advanced Waste Treatment Research
Laboratory, Cincinnati, Ohio 45226, 1970.
25. Weiss, "The Relative Significance of Phosphorus and Nitrogen as Algal
Nutrients". Water Resources Research. Institute Report No.
34, Chapel Hill, N. Carolina, 1970.
26. Wheatland, Barrett, and Bruce, A.M. "Some Observations on Denitrification
in Rivers and Estuaries". J. Proc. Inst. Sew. Purif. 149-162, 1959.
27. Wuhrmann, "High Rate Activated Sludge Treatment and Its Relation to Stream
Sanitation". I Pilot Plant Studies. Sewage & Industrial Wastes
(now Water Pollution Control Fed. J.) 1-27, 1954.
28. Wuhrmann, "Effects of Oxygen Tension on Biochemical Reactions in Sewage
Purification Plants" Advances in Biological Waste Treatment.
Proc. 3rd Conf. Biol. Waste Treat. 1960, pp. 27-38, 1963.
29. Wuhrmann, "Nitrogen Removal in Sewage Treatment Processes". Verh. Int. Ver.
Limnol., 15, 580-96, 1964.

22. Sawyer and Bradney, "Rising of Activated Sludge in Final Settling Tanks". Sew. Wks. J., 17, 1191, 1945.
23. Skerman and MacRae, "The Influence of Oxygen on the Reduction of Nitrate by Adapted Cells of Pseudomonas Denitrificans". Can. J. Microbiol., 3215-230, 1957.
24. Smith et al, "Nitrogen Removal from Municipal Wastewater by Columnar Denitrification". U.S. Department of the Interior Federal Water Quality Administration, Advanced Waste Treatment Research Laboratory, Cincinnati, Ohio 54226, 1970.
25. Weiss, "The Relative Significance of Phosphorus and Nitrogen as Algal Nutrients". Water Resources Research Institute Report 34, Chapel Hill, N. Carolina, 1970.
26. Wheatland, Barrett and Bruce, "Some Observations on Denitrification in Rivers and Estuaries". J. Proc. Inst. Sew. Purif. 149-162, 1959.
27. Wuhrmann, "High Rate Activated Sludge Treatment and Its Relation to Stream Sanitation", I Pilot Plant Studies. Sewage & Industrial Wastes (now Water Pollution Control Fed. J.), 1-27, 1954.
28. Wuhrmann, "Effects of Oxygen Tension on Biochemical Reactions in Sewage Purification Plants". Advances in Biological Waste Treatment. Proc. 3rd Conf. Biol. Waste Treat. 1960, 27-38, 1963.
29. Wuhrmann, "Nitrogen Removal in Sewage Treatment Processes". Verh. Int. Ver. Limnol., 15, 580-96, 1964.

TD	Nitrogen removal from
758.5	municipal wastewater /
.N58	Climenhage, D. C.
C55	78887